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The illustration shows the Babcock Fusion Welding Shop at our Renfrew Works.

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In virtually all types of pressure vessels, safety is a factor of paramount importance. The damage to life and property and the loss of production that may result from a single failure will justify, many times over, the relatively small additional cost of the best welding obtainable. The only class of welded fabrication applicable to pressure vessels whether for steam or dangerous chemicals, and which provides proof of safety in advance of use, is Babcock Class One Fusion Welding.

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All longitudinal joints and all circular joints must be subjected to X-ray examination to prove the soundness of the weld. This requirement is imperative in Babcock Class One Fusion Welding.

All pressure vessels are stress relieved after welding. This eliminates the tendency toward weakness and brittleness in welds not so treated, and removes the danger of localized corrosion. The vessel thus goes into service without inherent stress.

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The elongation of the weld metal itself must be not less than 20% in 2 inches.

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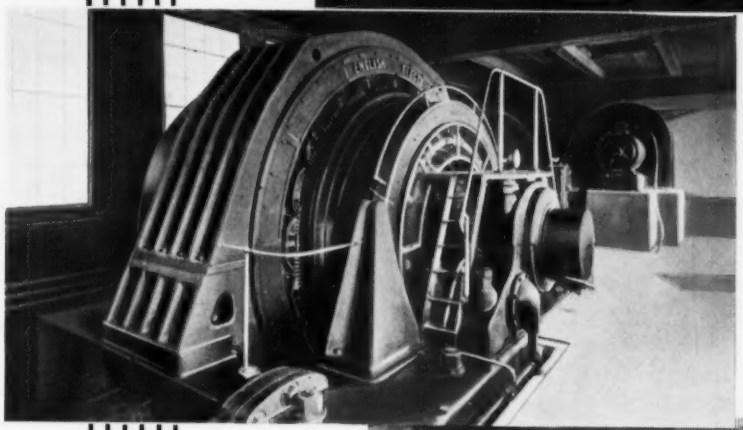

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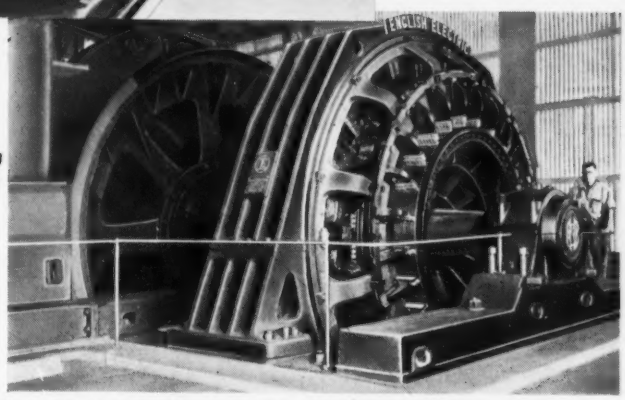

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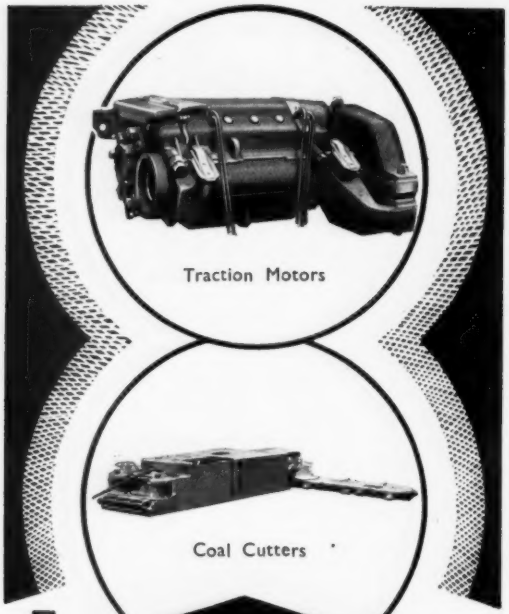

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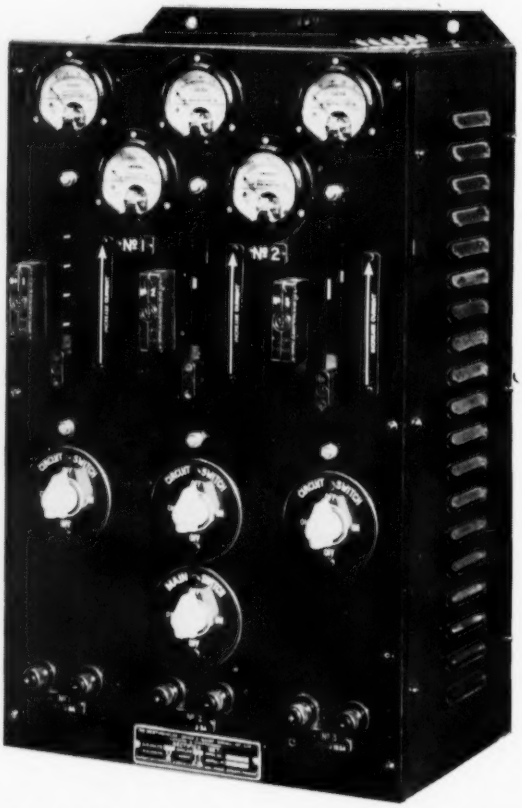

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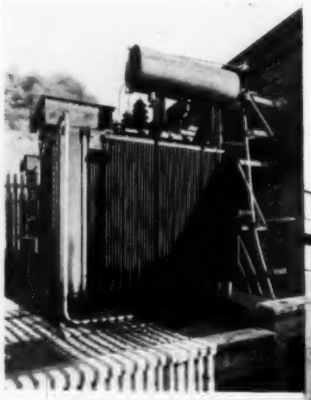

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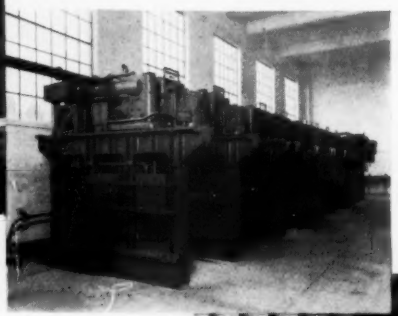

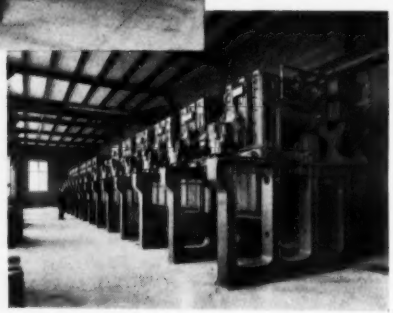

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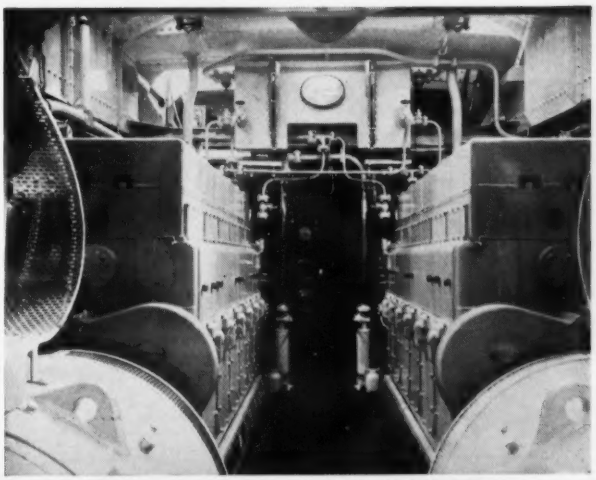

View of Engine Room showing part of the two 6-Cylinder 265 H.P., 530 R.P.M. Diesel Generator Sets

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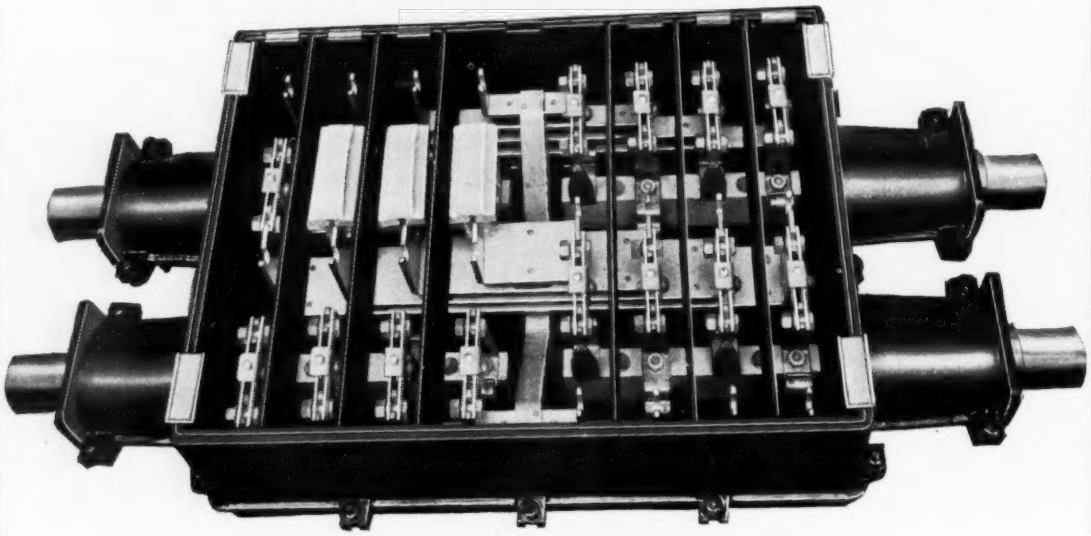

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The Diesel-Electric Tug "Framfield."

The English Electric Journal

Vol. VII. No. 5 APRIL, 1935 One Shilling.

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All Communications respecting Editorial Contents should be addressed to THE EDITOR, THE ENGLISH ELECTRIC JOURNAL, THE ENGLISH ELECTRIC COMPANY LIMITED, STAFFORD.

EDITORIAL.

In the January 1935 issue of this Journal we published an article giving the advantages and describing a Diesel-Electric Shunting Locomotive, and following on this, the first article in this issue deals with the application of the diesel-electric system of power transmission for Marine purposes.

Mr. Driskell's article describes the Diesel-Electric Tug "Framfield," which has recently been put into service on the Thames for barge towing duty. This type of propulsion for tugs has been received with great favour in America, where in recent years a large number of Diesel-Electric tugs have been put into commission. The results have proved that considerable economies can be obtained both as regards fuel consumed and maintenance charges.

The adoption, in this country, of diesel-electric propulsion for tugs is quite recent, the "Framfield" being the third vessel of this type to be constructed. It is

anticipated that this type of propulsion will be more widely used in the future. It will be appreciated that the duties of a tug necessitate very frequent and rapid manœuvring, and the diesel-electric system of propulsion is ideal for this class of duty, especially as the complete control of the vessel is in the hands of the navigator on the bridge.

A noteworthy feature of the "Framfield" is that the whole of the propulsion equipment has been manufactured by The English Electric Company, thus ensuring maximum co-ordination in its design and manufacture. The equipment includes Diesel engines, generators, main propulsion motor, auxiliary motors and control gear. The hull was built by Messrs. John I. Thornycroft, Southampton.

The second article, by Mr. R. M. Charley, deals with the design and applications of current-limiting reactors. After careful investigation the Company considers that the oil-immersed reactor is the most satisfactory type for a wide range of operating conditions. The Grid with its network of large power stations has introduced many new applications for current-limiting reactors.

The Company has had considerable experience in the design and manufacture of oil-immersed reactors, and is in a position to build units up to the largest sizes, and for the highest voltages.

A Cordial Invitation is extended to our readers to visit the Company's Stand at the following forthcoming Exhibitions.

BRITISH INDUSTRIES FAIR,
Birmingham.
May 20th to May 31st.
Stand No. C.613.

Exhibits will include a wide range of Industrial Fuse Gear, Domestic Heating and Cooking appliances, comprising Electric Cookers, Fires, Water Heaters, Irons and Washing Machines. In addition, there will be shown House Service Meters of the quarterly and prepayment types; Transformers for neon signs, portable and wall-mounting Transformers for low voltage lighting.

NATIONAL ELECTRICAL CONVENTION EXHIBITION,
Bournemouth.
June 4th to June 8th.
Stand No. 14.

A comprehensive range of Domestic Heating and Cooking appliances will be shown, including Electric Cookers, Fires of the Portable, Inset, Wall-type Surround and Mantel-Surround Type, Water-Heaters, Irons and Washing Machines. In addition, several new products will be exhibited.

The Diesel-Electric Tug "Framfield."

By T. W. DRISKELL.

The application of electricity to the propulsion of ships is not a new development, but it was not until recent years that it left the experimental stage and became fully established. One of the most popular and successful applications has been to tugs, and the latest example in this field is the barge-handling tug "Framfield," shown in the frontispiece. This vessel was built for the Thames Steam Tug and Lighterage Co., Ltd., by Messrs. John I. Thornycroft & Co., Ltd., Southampton, to the designs and specifications of Messrs. Constants, Ltd., who acted as consultants.

The whole of the propulsion equipment and auxiliary motors, together with the Diesel engines, were manufactured by The English Electric Co., Ltd., who thus hold a unique position in this respect, ensuring full co-ordination in the design and construction of all the equipment.

The results obtained by adopting this form of propulsion for tugs prove that it has many advantages over either the direct-driven Diesel tug or the steam tug. It will be appreciated that this class of vessel is called upon to perform certain operations which call for ease of operation, quick response and reliability in a high degree. Some of the more important advantages of the electric drive are :—

1. The propeller speed can be designed exactly to give the best towing results. Thus an increased tow-rope pull per B.H.P. of engines can be obtained.

2. The control of the vessel may be carried out directly from the bridge so that instant and accurate response is obtained.

3. Reliability and low maintenance costs are assured because the engines run under ideal conditions, i.e., they are unidirectional and run at constant speed. This leads to low maintenance costs, as the engines are not subjected to the repeated stopping and starting as in the case of the direct-drive engine. The reliability of electrical machines is well known, and their maintenance costs are extremely low.

4. The operating staff is very small as compared with a steam tug, one engineer only per shift being required. One engineer is sufficient because the control is carried out from the bridge and the engineer can devote the whole of his attention to the machinery.

5. The propeller speed and consequently the ship speed can be increased when not actually towing until the Diesel engine is fully loaded, although not running at over normal speed; consequently full use is made of the power available and time is saved when proceeding to a tow.

6. More than one generating set can be installed to drive one propeller and the propulsion motor may be of the double-armature type. This provides a complete stand-by, as 79 per cent. of full speed and one-half towing pull can be obtained even when one generating set of a two-engine tug is shut down. One-half of the propulsion motor can also be isolated and half power obtained from the other.

7. Economical running is obtained because the engines are running under the most efficient conditions. They can be shut down when not actually propelling the vessel, thus eliminating all stand-by losses.

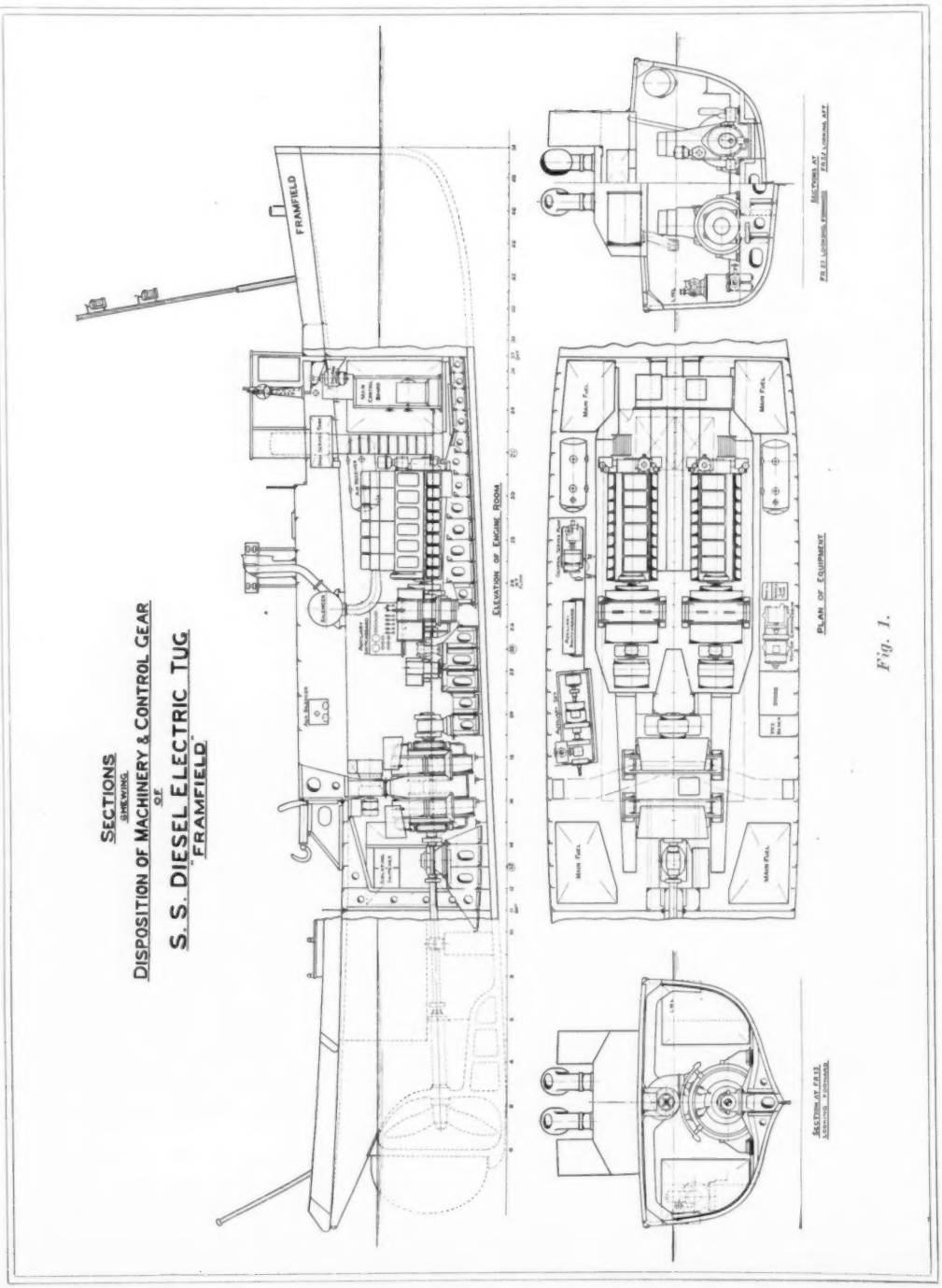

SECTIONS
SHEWING
DISPOSITION OF MACHINERY & CONTROL GEAR
OF
S. S. DIESEL ELECTRIC TUG
"FRAMFIELD"
FRAMFIELD
ELEVATION OF ENGINE ROOM
PLAN OF EQUIPMENT
SECTION AT FR 33
SECTIONS AT FR 51 LOOKING FWD & FR 67 LOOKING AFT

Fig. 1.

THE GENERAL ARRANGEMENT.

The " Framfield " is a single-screw vessel, and her principal dimensions are as follows :—

Length overall	83 ft. 0 in.
Length between perpendiculars	77 ft. 6 in.
Breadth	19 ft. 6 in.
Depth Moulded	10 ft. 4½ in.
Draught aft	10 ft. 0 in.

The hull is built of Siemens Martin mild-steel, and the scantlings are greatly in excess of the highest classification requirements of Lloyd's Register of Shipping, to which the vessel has been built. Experience has shown that for tugs operating on the Thames this is a very desirable feature.

The hull form has been built to plans specially prepared to meet the conditions of a maximum draught of 10ft., with a maximum height above the load line of 10 ft. 10 ins. These plans were prepared by Messrs. J. I. Thornycroft & Co., Ltd., in conjunction with Messrs. Constants to the special requirements of the owners' specification.

The machinery is situated amidships as shown in sectional arrangement Fig. 1, whilst Fig. 2 shows the engine-room looking forward. Accommodation for officers is provided forward in a comfortably furnished saloon with cushioned settees, table and lockers, and at the after end of the vessel there is a crew's messroom arranged with an entrance both from the engine-room and the deck. It is fitted with seat lockers, mess table, cooking and warming stove. This room is also used to store the navigation lamps, equipment, etc.

The counter stern is of cast-steel in one piece from the transom right aft ; this ensures adequate strength at a point where most of the blows are taken during barge handling. It will be seen from the general arrangement drawing, Fig. 1, that the keel has been cut away below the stern tube to allow the water to flow through when the vessel is turning ; this is termed a " sluice keel " and ensures ease of steering and manœuvring. This has proved very successful, as will be seen from the results obtained at the official trials.

The bulwarks are low and very strongly constructed with considerable " tumble home," and the casing is of reasonable height, with lighting and ventilating skylight flaps. The engine-room entrances are built up to full height on each side, just aft of the bridge, which is placed over the top of the fore end of the casing and is completely enclosed in teak.

The bridge is fitted with telegraphs operating the main controller in the engine-room. This gives the control of the vessel directly in the hands of the navigator. The necessary indicating lights and instruments are also mounted in the bridge ; these include an indicator showing the speed in R.P.M., ahead and astern of the propeller, and a " Tyfon " compressed air whistle.

The steering gear for the vessel was made by Messrs. Thos. Reid & Sons (Paisley), Ltd., and is operated electrically by means of a vertical spindle motor. The mechanism is placed on the bridge and is connected to the rudder by chains and rods. The motor is placed in the engine-room, immediately below the bridge, where it is

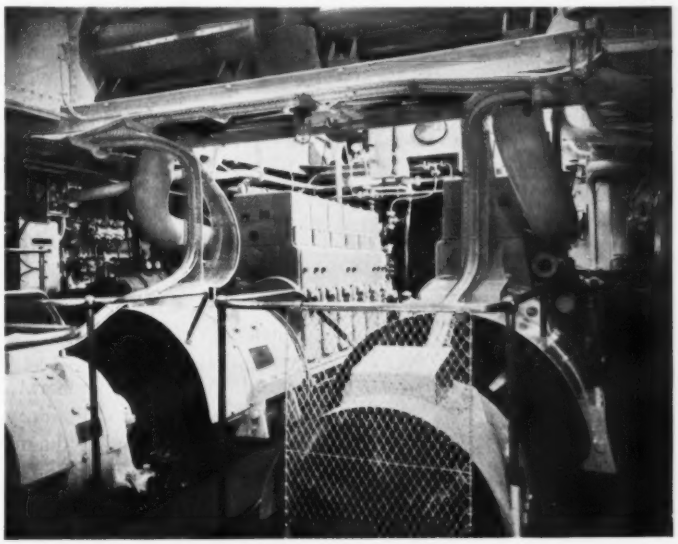


Fig. 2.—Engine-room, looking Forward.

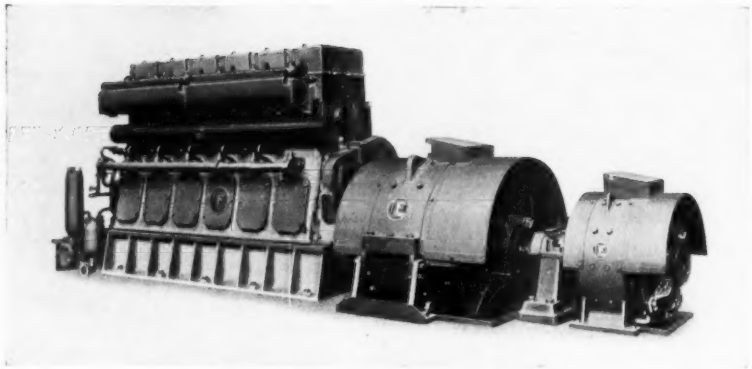


Fig. 3.—One of the 265 B.H.P. Diesel Generator Units.

fully protected. The mechanism is so arranged that direct hand steering can be used.

The appearance of the vessel is distinctive, as there is no funnel. It will be noticed from the frontispiece photograph that two engine-room ventilators are placed abaft the bridge ; these are arranged with the exhaust pipes through the centre and emerging at the top. This arrangement gives an unobstructed view in all directions from the bridge—a valuable feature when handling barges. At the same time the vessel is able to pass under low bridges without the necessity of lowering a funnel.

The main fuel supply is carried in four separate fuel-storage tanks placed at the four corners of the engine-room. These tanks have a total capacity of about 12 tons, which is ample for one week's service without re-fuelling. The engines themselves are fed by gravity from a daily service tank ; this tank is divided, each half supplying one engine, the total capacity of the tank being approximately $\frac{3}{4}$ ton.

The engine seatings were specially designed to give a very strong and rigid structure in order to reduce vibration to a minimum. This has proved very successful, as the engines are remarkably steady and free from vibration.

The vessel is fitted with electric heaters in the fore cabin and on the bridge. Electric lighting has been installed throughout. An interesting feature of the electric navigating lights is a special warning device. This consists of relays operating a warning bell and indicating lamps arranged so that if a navigating light should fail the bell rings and an indicating light shows which lamp has gone out.

ENGINES.

Two 265 B.H.P. Diesel engines provide the power for propulsion ; they are each of the " English Electric " six-cylinder solid injection type running at 530 r.p.m., with a bore of 10 in. and stroke 12 in. They are fitted with individual C.A.V.-Bosch fuel pumps for each cylinder, all controlled by the main governor ; the camshaft is chain driven from the flywheel end of the engine, and the governor is driven from the opposite end of the camshaft. The valves and valve seats are carried in separate cages so as to be easily removable, and it will be seen from the illustrations that the whole of the valve gear and fuel pump mechanism is totally-enclosed. This gives the engines a very clean appearance and reduces noise.

The engines are started on all six cylinders by compressed air at 350 lb. per sq. inch. This is contained in two receivers of ample size, and on trial it was found that with twelve successive starts of one engine from one receiver the pressure only dropped to 219 lb. per sq. inch.

The engines drive their own circulating water and the bilge pumps. These are of the reciprocating marine type driven through gearing from the crankshaft at one-third engine speed.

GENERATORS.

Each of the Diesel engines is directly coupled to a 168 kW. main generator and 25 kW. auxiliary generator in tandem, as shown in Fig. 3. Each main generator has a full load voltage of 350 volts. The auxiliary generators are designed for 110 volts and supply the excitation of the main motor and part of the excitation for the main generators, in addition to the auxiliary load and lighting. One auxiliary generator is sufficient for the whole of the load, the other being stand-by.

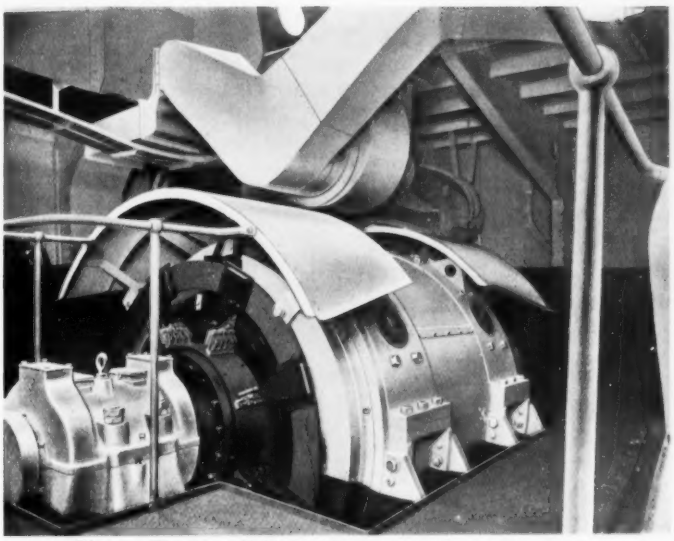


Fig. 4.—The 400 S.H.P. Double-Armature Propulsion Motor.

The magnet frames of the generators are of fabricated construction and the main generator frames are rotatable and carried in cradles. This enables the bottom poles to be inspected and removed if required without dismantling the machine or removing the rotor.

Propulsion Motor.

The propulsion motor is of the double-armature type and carried in cradles in the same manner as the main generators. The double-armature type of motor is small in diameter for its output ; this saves a considerable amount of space and enables the motor to be mounted low down in the vessel and avoids the propeller shaft being raked at a large angle. In addition to this, it affords added reliability to the equipment, as one half can be disconnected and half power obtained from the other. Fig. 4 shows the motor installed on the vessel.

The two armatures are mounted on a "through" shaft, which has a forged-on coupling at one end for bolting to the " Michell " thrust block which also incorporates the after-end bearing of the motor.

The propulsion motor and generator bearings are disc-lubricated, the motor bearing having two discs, one each end of the journal as shown in Fig. 5, and the oil is fed to the centre of the bearing by a special type of slipper carried on the rim of each disc at the top. This bearing has proved very successful in operation and provides ample lubrication at all speeds, both ahead and astern.

Control System.

The control of the propulsion motor is on the well-known " Ward Leonard " principle whereby its speed and direction of rotation are changed by varying the strength and polarity of the generator fields. By using this system it is possible to control the ship without switching operations in the main heavy current connections between the dynamos and driving motors. The generators and propulsion motor armatures are connected in series in the manner shown on the diagram of connections, Fig. 6. Each generator is connected through a cut-out switch (not used for control operations) so that the motor can be operated from either of the two generators or both together.

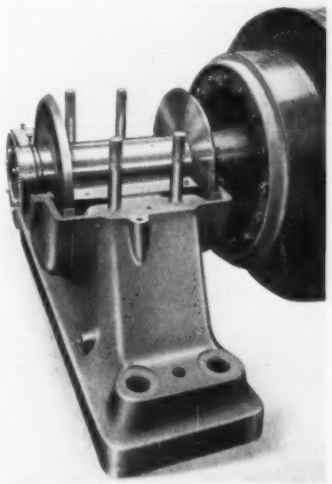
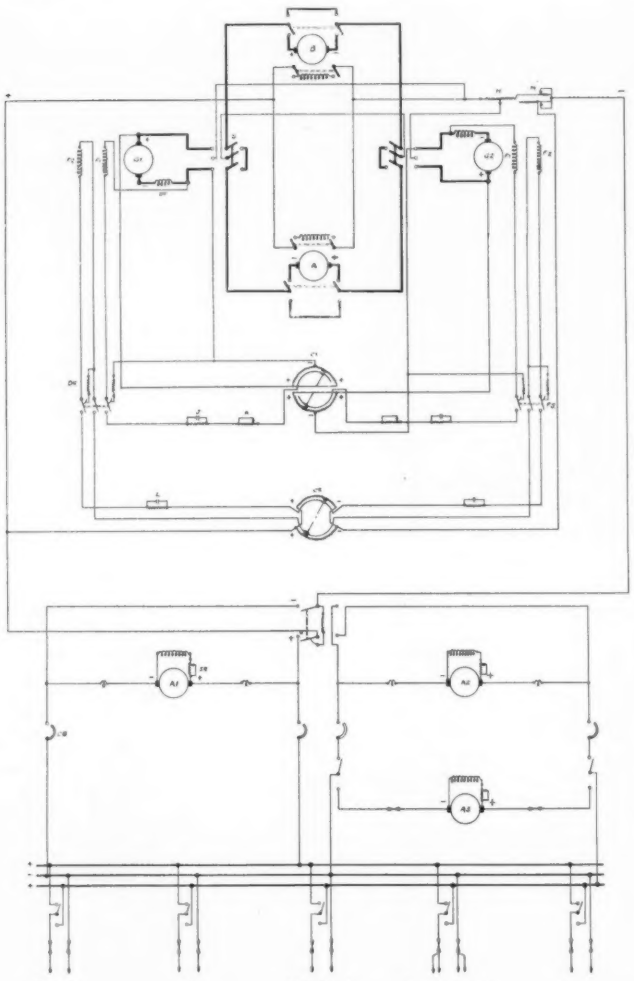


Fig. 5.—Propulsion Motor Bearing, showing special lubricating discs.



A = *Aft Motor.*
B = *Forward Motor.*
G1 = *Port Generator.*
G2 = *Starboard Generator.*
CB = *Circuit Breaker.*

A1 = *Port Aux. Generator.*
A2 = *Starboard Aux. Generator.*
A3 = *Emergency Generator.*
DR = *Discharge Resistance.*
S = *Generator Cut-out Switch.*

F1 = *Self Excited Field.*
F2 = *Sep. Excited Field.*
C1 = *Potr. Regr. for self Excited Fields.*
C2 = *Potr. Regr. for sep. Excited Fields.*
SF = *Series Field.*
H = *Resistance for Motor Field weakening.*
J = *Reducing Resistance for Gen. Field.*
K = *Regulator for Self Excited Field.*
L = *Regulator for Sep. Excited Field.*
M = *Regulator for Motor Fields.*
FS = *Field Switch.*

Fig. 6.—Schematic diagram for Electric Propulsion Equipment.

It will be appreciated that Diesel engines are only capable of a limited overload, and in order to maintain full-load conditions under normal working, means must be provided to prevent the propeller from imposing undue overloads such as would stall the engines, either during manœuvring or in case the propeller became fouled or entangled. This protection is carried out in the following manner.

The generators have been designed with three field circuits to give de-compounded characteristics, these fields consisting of a separately excited shunt field, a self-excited shunt field, and a negative series field. Under normal operation the negative series winding overcomes part of the shunt winding, the remainder being sufficient to produce the required field. Should the propeller cause an overload to be imposed on the motor the extra current in the series winding overcomes a greater proportion of the shunt winding and so reduces the voltage at the terminals of the generator, thus preventing an excessive current flowing between the generators and the motor and also preventing any overloading of the engines.

The two shunt fields are varied in strength to give varying speeds of the propeller, and the separately excited shunt field is reversed as well when it is required to reverse the propeller. Both fields are controlled by the main controller, which is placed in the engine room; the controller face-plate is illustrated in Fig. 7. The complete control of the tug is carried out from the bridge on which is mounted two standard type ships' telegraphs, giving control from both sides of the bridge. These are cross connected mechanically so that

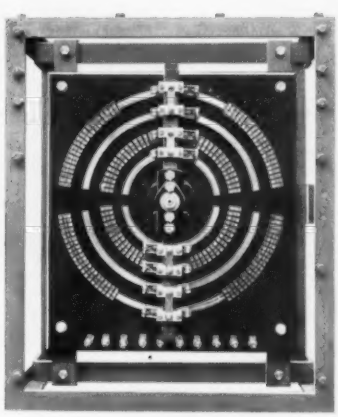


Fig. 7.—Propulsion Control Regulator.

they work together, and the connection is continued down to the engine room on to the controller, which is mounted on top of the control board. These connections are by shaft and bevel wheels. On reaching the control board the final connection to the controller is by chain through a clutch mechanism. This clutch mechanism is arranged so that the bridge control can be isolated and the controller connected to a handwheel on the control board. There is a further handwheel on the controller shaft itself to enable control to be maintained should the chains break.

The main control board is shown in Fig. 8, and its position in the engine room can be seen in Fig. 9; it is of the dead front type and consists of four-sheet steel panels. Two of these control the two main generators, one controls the propulsion motor and one the two auxiliary generators. The generator panels are fitted with a main cut-out switch arranged to "make" before "break," so that the machine can be isolated without shutting down the propulsion motor. The method being to open the field-switch first and when the voltage has dropped to about zero the cut-out switch is operated. In order to prevent incorrect operation, an interlock is fitted to ensure that the field switch is opened first and closed last. In addition, to ensure that a reasonable time has elapsed to enable the field to die away, a special catch has been provided to stop the cut-out switch in the mid position, when the catch is released the switch can be finally closed.

The motor panel is provided with a combined regulator for the motor and generator fields arranged to maintain the motor field constant, whilst inserting a resistance in the generator fields to compensate for their cold and hot condition and to maintain the generator field constant whilst inserting a resistance in the motor field for adjusting the speed of the propellers.

The operation is by a common handwheel and the regulator is operated in conjunction with an over-current relay and lamp, which warns the engineer when the current has exceeded a predetermined figure and the field regulator requires adjustment.

The auxiliary generator panel is fitted with breakers and an excitation changeover switch to enable excitation to be carried by either auxiliary generator. The power required for auxiliary motors, lighting, etc., is controlled by a separate small distribution panel, placed along the port side of the vessel; this panel is illustrated in Fig. 10.

Fig. 8.—Main Control Board.

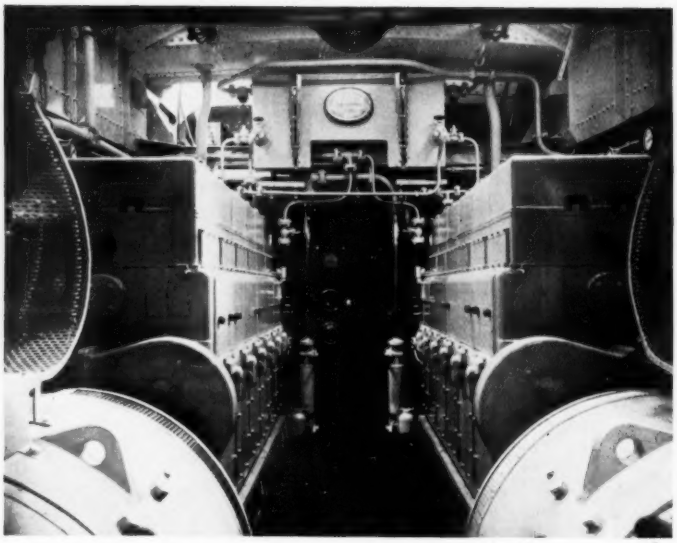


Fig. 9.—Engine-room, showing position of Main Control Board.

All the essential parts of the equipment have been suitably interlocked to make it as mistake-proof as possible, and earth indicating lamps have been provided for all circuits.

Auxiliary Machinery.

The necessary engine-room auxiliaries have been provided and placed along the sides of the vessel. A stand-by generating set, illustrated in Fig. 11, is installed, which consists of a 10 H.P. Petter engine driving a 5 kW. generator, and a compressor, which is provided with a clutch so that it can be disconnected when not required. In addition to this, there is a motor-driven compressor for use when the main engines are running. A general service pump is provided for deck use and for supplying the engines with circulating water if required. The fuel is transported from the main tanks to the daily service tanks by a motor-driven fuel-transfer pump, which has a small hand-operated pump as standby.

Cables.

The main cables are lead covered and armoured, and were manufactured by Messrs. Siemens Brothers, Woolwich. They are carried in perforated trays supported from the deck beams. The auxiliary cables were supplied through Messrs. Siemens Electric Lamps & Supplies, Ltd., by British Insulated Cables, Ltd. The whole of the cable work, together with the lighting installation, was carried out by Messrs. John I. Thornycroft & Co., Ltd.

Reference to Figs. 2 and 9 will show that the design of the engine-room is very compact and gives ample space for attending to the plant, every part is easily accessible and, due to the fact that the whole of the machinery has been painted in a cream colour, a very light and pleasant engine room has been obtained. A notable feature is the lack of noise, particularly from the exhaust when observed from the bridge, and also the very clear exhaust gases.

Trials.

Official trials were held at Southampton on February 27th, and towing trials, with further dock trials, were held on the Thames on March 26th and April 1st. The results are particularly gratifying, especially the horse-power per ton pull on the towrope, which is the figure which

Fig. 10.—Stand-by Generator Control and Main Feeder Board.

will indicate the future economy of the vessel in service. The manœuvrability and ease of control were particularly noted, and the vessel answered to the steering in a very satisfactory manner. Both the telegraph and the steering wheel are extremely light to handle.

The trials were carried out with experimental cast-iron propellers, one designed for 100 R.P.M. when towing, and another for 130 R.P.M. when towing. This was done in order to determine the best design for towing conditions obtaining on the Thames. The final propeller will be made from bronze.

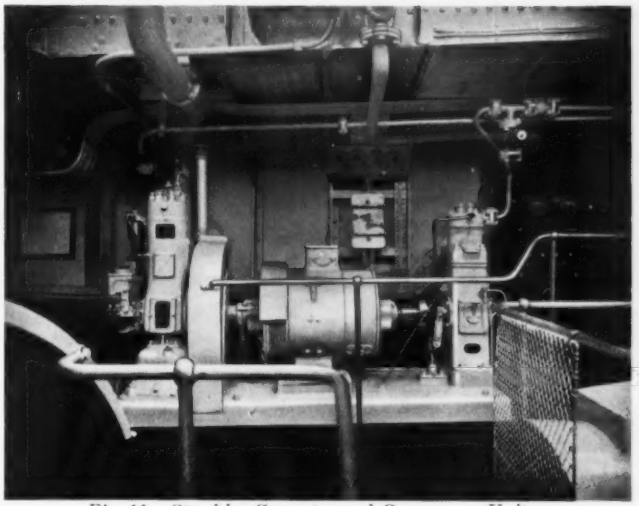


Fig. 11.—Stand-by Generator and Compressor Unit.

Table A gives the results of the free running speed and manœuvring trials carried out at Southampton with the 100 R.P.M. propeller. Tables B and C give the towing trial results carried out on the Thames with 100 R.P.M. and 130 R.P.M. propellers respectively.

TRIAL RESULTS OF DIESEL-ELECTRIC TUG "FRAMFIELD."

TABLE A.

FREE RUNNING TRIALS WITH 100 R.P.M. PROPELLER.

SPEED ON MEASURED MILE.

	Time. Mins. Secs.	Speed. Knots.	Mean Speed. Knots.
Full ahead, both engines	6 13	9.651	9.893
,, ,, ,, ,, ...	6 2	9.945	
,, ,, ,, ,, ...	6 5½	9.849	
,, ,, ,, ,, ...	5 55½	10.126	
Full ahead, one engine	6 55	8.675	8.276
,, ,, ,, ,, ...	7 37	7.877	

MANŒUVRING WITH ELECTRIC STEERING IN OPERATION.

	Time.
Complete circle on Port helm at full speed	1 min. 15 secs.
,, ,, ,, Starboard helm at full speed	1 min. 14 secs.
Vessel full speed ahead to vessel stopped with propeller turning astern ...	26 secs.
Vessel full speed astern to vessel stopped with propeller turning ahead ...	22 secs.
Propeller turning 120 R.P.M. ahead and vessel under full way to propeller turning astern	5 secs.
Propeller turning 120 R.P.M. astern and vessel under full way to propeller turning ahead	5 secs.

TABLE B.

TOWING TRIALS WITH 100 R.P.M. PROPELLER.

Barges	"Minster"	217 tons	D.W. Coal.
	"Custodian"	214 ,,	,, ,,
	"Judge"	223 ,,	,, ,,
	"Gasoven"	200 ,,	,, ,,
		854 tons.	
	Barges total ...	275 tons.	
	Total tow ...	1,130 tons.	

	Time. Mins. Secs.	Pull tons.	Knots.	Tow Rope H.P.
Towing four Barges—				
With tide	12 50	4.75	4.675	
Over tide	13 19	4.8	4.516	
Mean		*4.77*	*4.59*	*151*
Towing two Barges ("Judge" and "Minster")				
With tide	7 18	4.25	8.21	
Over tide	16 48	4.25	3.57	
Mean		*4.25*	*5.89*	*172*

TABLE C.

TOWING TRIALS WITH 130 R.P.M. PROPELLER.

Barges	"Custodian"	214 tons	D.W. Coal.
	"Gaslight"	219 ,,	,, ,,
	"Discoverer"	199 ,,	,, ,,
	"Gasoven"	200 ,,	,, ,,
		832 tons.	
	Barges total ...	280 tons.	
	Total tow ...	1,112 tons.	

	Time. Mins. Secs.	Pull tons.	Knots.	Tow Rope H.P.
Towing four Barges—				
With tide	13 43	5.25	4.38	
Over tide	14 11	5.10	4.23	
Mean	*13 57*	*5.175*	*4.305*	*153*

TABLE C.—(*continued*).

	Time Mins. Secs.	Pull tons.	Knots.	Tow Rope H.P.
Towing two Barges (" Gaslight " and " Discoverer ")				
With tide	7 25	4.4	8.09	
Over tide	15 5	4.3	3.79	
Mean	*11 37½*	*4.35*	*5.94*	*178*
Towing one Barge (" Discoverer ")				
With tide	5 47	3.6	10.375	
Over tide	12 26	3.6	4.82	
Mean	*9 6½*	*3.6*	*7.597*	*188*

TABLE D.

STANDING PULL TRIALS WITH 100 R.P.M. PROPELLER.

No. of Engines.	S.H.P.	R.P.M.	Pull tons.	S.H.P. per ton pull.	B.H.P. per ton pull.
2	385	98	6.3	61	71
1	195	75	3	65	76

WITH 130 R.P.M. PROPELLER.

No. of Engines.	S.H.P.	R.P.M.	Pull tons.	S.H.P. per ton pull.	B.H.P. per ton pull.
2	380	116	7.1	53.6	62.5
2	417	118	7.125	58.4	68

Current-Limiting Reactors. Their Design and Application.

By R. M. CHARLEY, M.C., B.Sc., M.I.E.E., Mem.A.I.E.E.

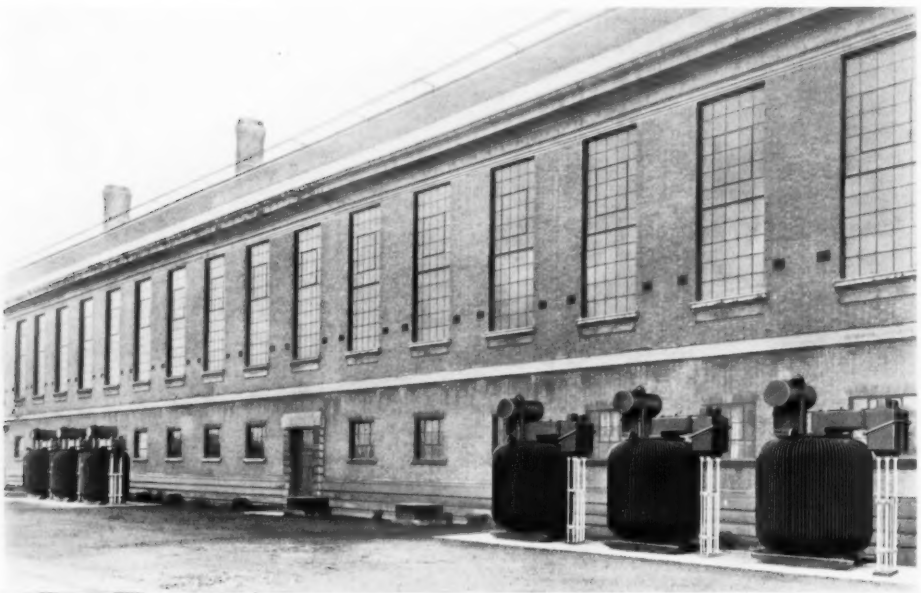


Fig. 1.—Two of five, 6,000 kVA., 33 kV. banks of Reactors installed at the Barking Power Station of the County of London Electric Supply Company.

Reactance in an alternating current circuit is one of the characteristics that cause voltage drop with its attendant problems which are becoming more and more urgent, but this same feature has a very real value in that it limits the amount of current that can flow in the circuit under short-circuit or earth-fault conditions. In the early days of the application of alternating current to electrical distribution, the question of voltage regulation was predominant, and transformers, even up to comparatively large sizes, were built with reactance values as low as 2 per cent. or even less. This practice was quite natural, for it was realised that good voltage regulation was desirable, but little experience had been gained as to the effects of short-circuits on the system and connected apparatus. Practice has changed radically, until to-day the values of reactance for transformers are chosen on the basis of the minimum value that will allow the transformer to withstand the mechanical stresses due to short-circuit, and these values are as high as 10 per cent. or even 12 per cent. In these cases the voltage drop that results is compensated for by on-load tap-changing equipment on the transformers or by some form of separate voltage regulator. In spite of the increased circuit reactance which is now usual, the insertion of additional reactance is quite often necessary.

The most usual application of a current-limiting reactor is where the conditions on the system result in a short circuit kVA. beyond the rupturing capacity of the installed switchgear. Much knowledge has been gained in recent years as to the capability of a switch of rupturing a short-circuit current, and in many cases it has

been found that existing switches do not have the rupturing capacity originally expected. Systems have extended and more generating plant has been installed, thus increasing the possible short-circuit kVA. Hence it has been necessary to carry out careful investigations into the characteristics of the system to determine the relation between the worst possible fault condition and the capacity of the switchgear to deal with it.

To replace the existing switchgear with new equipment of greater rupturing capacity is often an expensive matter, though there may be circumstances when this course is justified. It may be possible, in some cases, to increase the rupturing capacity of the switches by some modification such as the replacement of the existing contacts with new ones of the " De-Ion Grid " type. The most usual procedure, however, is to install current-limiting reactors, the effect of which is to limit the short-circuit current to a value that can be safely ruptured by the switchgear.

Fig. 2.—Tank for Reactor showing special arrangement of cable boxes.

Reactors are sometimes connected between generators and the busbar ; or they may be inserted between sections of the busbar, in which case it is clear that under normal conditions no current flows through the reactor. The majority of applications have the reactors connected in the individual feeders leaving a main station or a substation.

The effect of the reactor on the voltage of the system is usually not serious. Fig. 3 shows the vector diagram for a case where a reactor having a value of 5 per cent. is connected in a circuit in which the power factor of the load is 0.8. The reactor voltage is almost wattless, and hence the vector V_r is at right angles to the load current vector I, and the resultant voltage is V_1. The voltage drop in the circuit is only 3 per cent. In general, unless very high values of reactance are necessary, the voltage drop due to the insertion of the current-limiting reactor may be neglected. The vector diagram is not drawn to scale, as the values would be too small to illustrate the point.

A current-limiting reactor must be designed so that it does not lose any of its effectiveness as the current through it increases up to the short-circuit value ; in other words, the curve relating current and reactance must follow a straight line as closely as possible. It is only natural, therefore, that the simplest design is one in which the leakage flux path is entirely in air. In some instances the reactor is assumed to be the only effective reactance in the circuit, e.g., the short-circuit current in a circuit containing a 5 per cent. reactor is 20 times normal current. It is more usual, however, to assume that there is some reactance in addition to that of the reactor, e.g., the short-circuit current in the above-mentioned case is less than 20 times normal. In any event,

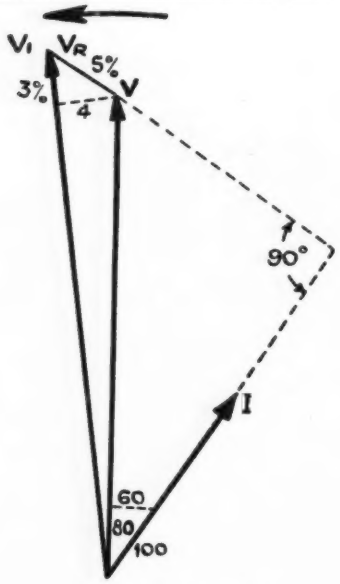


Fig. 3.— Vector Diagram.

the reactor must be designed to limit the current to the predetermined value under the worst circuit conditions.

The earliest air-core reactors were made in various forms. A construction sometimes used was one in which a lead-covered cable was wound in a spiral coil and completely embedded in a concrete block. This design, while having great mechanical strength, had severe limitations as regards current rating on account of the poor cooling efficiency. More commonly the reactor was wound as a spiral coil with its axis vertical, the conductor being a stranded cable, sometimes bare or wrapped with asbestos or other insulation. The turns and layers of the coil were spaced, and supported in various ways. In some designs the coil was wound on a former with temporary spacers, and then certain portions were filled in with concrete, thus forming solid supports for the turns and leaving sufficient exposed cable to provide adequate cooling. In other designs the concrete supports were replaced by cleats of porcelain, or some hard insulating composition usually with an asbestos base, these cleats being placed in position during the winding process and finally bolted together vertically by means of tie bolts of non-magnetic material.

The modern design of air-core reactor is known as the Concrete Disc type, a typical example of which is illustrated in Fig. 4. In order to reduce eddy current losses in the conductor to the minimum, each strand of the cable is enamelled, but there is no further covering; thus the maximum cooling effect is obtained. The coil is wound with horizontal and vertical spacers formed of a very hard insulating material, and after completion the whole coil is dipped in bakelite varnish and baked, the result being a very solid and well-insulated coil. Finally, the coil is placed between two heavy concrete discs bolted together with axial bolts of non-magnetic material. The bottom disc is supported on insulators arranged for bolting to the floor. The ends of the conductor are brought out to copper bars fixed to the concrete discs. For heavier currents the conductor may comprise two or more cables in parallel.

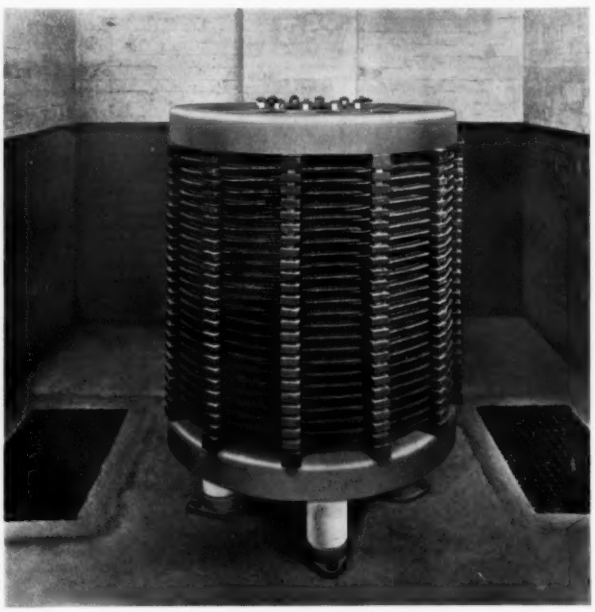


Fig. 4.—Typical Concrete Disc Type Reactor.

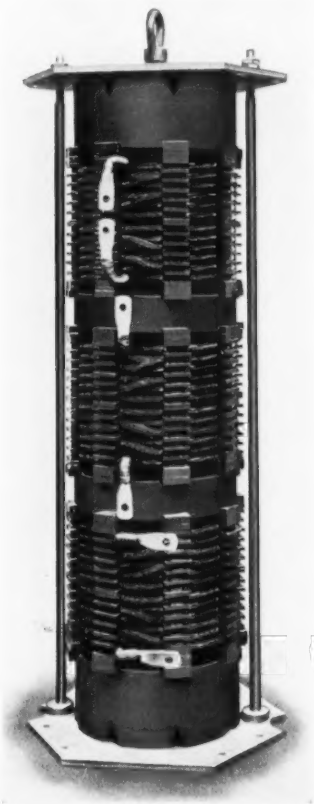


Fig. 5a.—3-Phase Magnetic Shielded Reactor (without Shields).

This type of reactor is perhaps the most economical to construct, but it has several serious drawbacks. Such reactors are not suitable for outdoor service. Since the influence of the leakage field is unrestricted, care must be taken that magnetic material, such as the structural steel members of the building, whether exposed or concealed, must be kept outside a certain minimum distance from the coil. An approximate rule for this clearance is that it should be at least equal to one-half of the outside diameter of the coil. Under short-circuit conditions, the magnetic forces between adjacent reactors may be very great, and hence the distance between them should not be less than the outside diameter of the reactor and they must be bolted very securely to the floor. These features mean that the installation of air-core reactors may be a costly matter, offsetting very largely the possible saving in initial cost of the reactors, as compared with the present almost universal practice of the adoption of reactors of the oil-immersed type.

It is suggested that fundamentally the use of the air-core type of reactor is not consistent with the present common practice of making the entire system iron-clad or totally-enclosed. The reactor is installed solely as a protection, and hence surely it should be made in accordance with the best known principles. Accordingly, modern practice tends very strongly to the adoption of oil-immersed reactors, which, although more expensive, have the greatest possible reliability and can be installed out-of-doors.

It follows from the previous statements regarding the unrestricted influence of the leakage flux of air-core reactors, that the serious problem

Fig. 5b.—3-Phase Magnetic Shielded Reactor (with Shields).

in the design of oil-immersed reactors is to prevent the flux penetrating the tank-side, causing very heavy losses and serious heating. This can be achieved by a combination of judicious spacing, and the provision of shields between the coil and the tank.

There are two designs, commonly known as the Magnetic Shielded type and the Ironclad type, respectively, each having its particular application depending on the characteristics of the reactor.

In the Magnetic Shielded type of reactor the shields are formed of packets of laminations of transformer-steel clamped solidly to prevent vibration and mounted at an appropriate distance from the coil, the plane of the laminations being vertical and at right angles to the surface of the tank. In the larger sizes the shields are mounted on the wall of the tank, but for smaller units they are supported in wooden frames around the coil itself. This construction allows the assembly of three coils in a three-phase bank of comparatively small capacity, vertically on the same axis, thus minimising the floor space required. An example of such a three-phase reactor is illustrated in Fig. 5 (*a*) without shields, (*b*) with shields.

The winding and insulation of Magnetic Shielded reactors is similar to that described for the Concrete Disc type, but the complete coil is clamped between substantial plates of steel with phosphor-bronze bolts, insulation and adequate spacing between the coil and the plates being obtained by means of substantial collars of bakelised paper.

Fig. 6 shows the coil of a current-limiting reactor which is one of the largest ever built. A three-phase bank gives 12 per cent. reactance on 50,000 kVA. in a 33 kV. 50-cycle circuit. The equivalent normal rating of the three-phase reactor is therefore 6,000 kVA. Five of these are connected between sections of the 33 kV. busbar in the Barking Power Station of the County of London Electric Supply Company, Ltd. The magnetic shields are mounted inside the periphery of the tank. Cooling surface for dissipating the losses is provided by elliptical tubes bent on edge and welded into the tank-side. This construction is unique, and it enables a much greater amount of cooling surface to be obtained on a certain size of tank than is possible with round tubes. This feature is adopted with great advantage in transformer design. The arrangement of the tank and cable boxes is shown in Fig. 7.

An Ironclad reactor is illustrated in Fig. 9. The construction is very similar to a transformer of the single-phase three-limb core type, but the centre limb on which the coil is mounted is formed of non-magnetic material instead of laminations of steel.

In the Magnetic Shielded and Ironclad type of reactors transformer steel laminations are used

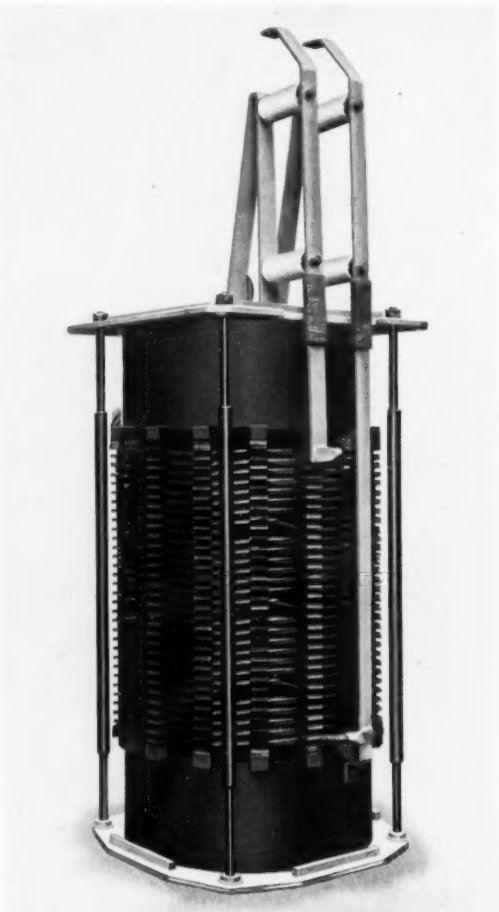


Fig. 6.—Coil as used in the Reactors illustrated in Figs. 1 and 7.

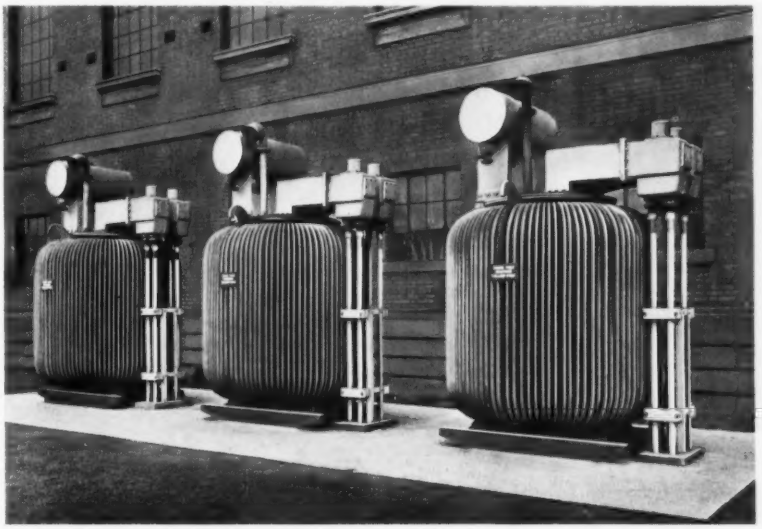


Fig. 7.—Reactors installed at the Barking Power Station (see Fig. 1).

Fig. 8.—One of a number of banks of Reactors installed at the North Tees Power Station of the North Eastern Electric Supply Company.

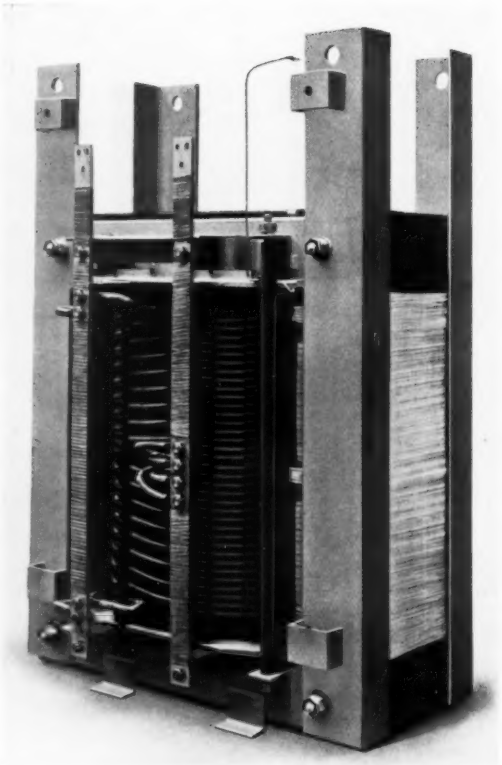


Fig. 9.—Ironclad Type Reactor.

as the shields, forming low reluctance paths for the flux outside the coil, thus preventing the stray flux from entering the tank. The laminations become saturated under short-circuit conditions, and the reactor then functions as an air-core reactor. The characteristic curve is shown in Fig. 10. It is a straight line above which a small excitation curve is superimposed ; up to several times full load current the reactance is slightly greater than for an air-core reactor, above which point the curve is parallel to the straight line for the air-core coil.

An important feature in the design of the winding of reactors is the ability to withstand the mechanical stresses produced under short-circuit conditions. The force due to current flowing in the conductor is proportional to the square of the current. There is a radial force tending to increase the diameter of the winding, but the tensile strength of the conductor is great enough to withstand this stress. The serious force in the winding is that tending to reduce the axial length, which, consequently, exerts a bending force on the conductor between the spacers. Care must be taken to ensure that the construction is safe in this respect, otherwise short circuits between turns may occur.

The thermal design of a current-limiting reactor is a very important consideration. Under normal load conditions the loss generated must be dissipated by radiation from the cooling surface of the tank in order to keep the temperature rise of the winding below 55° C. The loss is proportional to the square of the current ; hence, when a short-circuit occurs, the loss is many times that of the loss at normal load, and heat is generated so quickly that little of it can escape from the conductor and consequently the temperature of the copper rises at a very rapid rate. The maximum temperature permissible at the end of the short circuit is 250° C. It is usually assumed that the reactor shall be capable of withstanding the short-circuit conditions for five seconds.

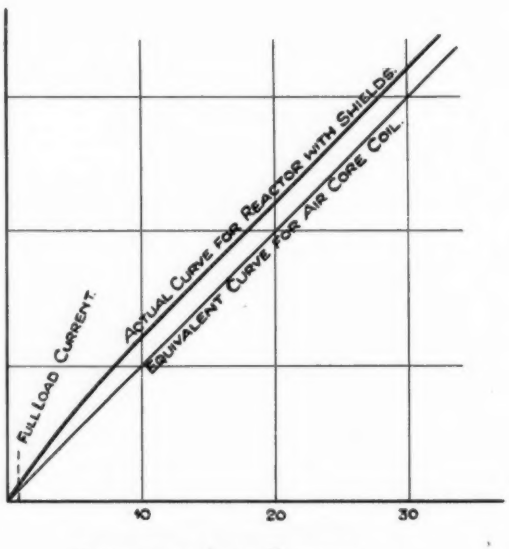


Fig. 10.—Characteristic Curve for Reactor with Shields.

The ratio between the normal current and maximum short-circuit current has a big influence on the thermal design of the reactor. For instance, if the reactor is to give 5 per cent. reactance and no other reactance is in the circuit, the short-circuit current is twenty times normal, in which case the short-circuit conditions probably determine the thermal design. But if there is additional reactance in the circuit so that the maximum short-circuit current is only, say, twelve times normal, then normal load conditions have the greater influence on the design. This feature is also affected by the policy as regards normal load loss. In order to save running costs it may be desirable to reduce the load loss to a comparatively low value by the use of a bigger conductor, which naturally improves the thermal conditions under short-circuit.

Fig. 11.—Coils for small 3-phase Oil-immersed Reactor.

The temperature rise during the time of short-circuit can be calculated from the following formula :—

$$Tf = At \left[\frac{B}{2Ta} + \frac{618.4\ K}{B} \right] + Ti$$

where

Tf = final temperature, in ° C.,
Ti = initial temperature, in ° C.,
Ta = absolute initial temperature (Ti + 234.5),
t = duration of short-circuit, in seconds,

$$K = \text{ratio } \frac{\text{eddy current loss}}{I^2R \text{ loss}} \text{ at } 75^\circ \text{ C.}$$

$$A = \frac{\text{watts per lb. at Ti } ^\circ \text{ C.}}{180}$$

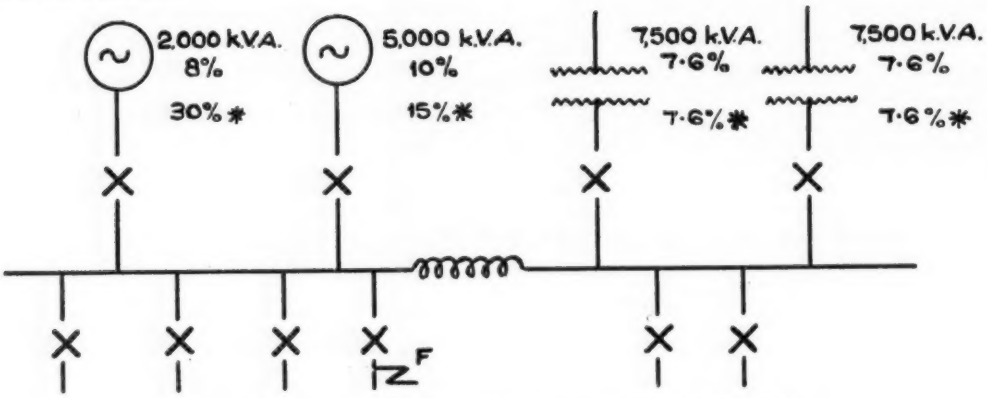
B = 2Ta + At.

Tanks, bushings and cable boxes of reactors follow very closely usual transformer practice. Based on the principle that a current-limiting reactor is installed solely to protect the system, no precaution should be neglected to ensure the greatest possible reliability. Therefore the tank is equipped with an expansion vessel so that it is completely filled with oil, the di-electric strength of which is thus maintained at a high value.

In addition to the various applications of current-limiting reactors mentioned at the beginning of this article, the vast network of interlinks at 132 kV. and 66 kV. now covering this country will probably bring problems necessitating the installation of reactors. Such requirements can be met for there is practically no limit to the size and voltage for which current-limiting reactors of the type described above can be built.

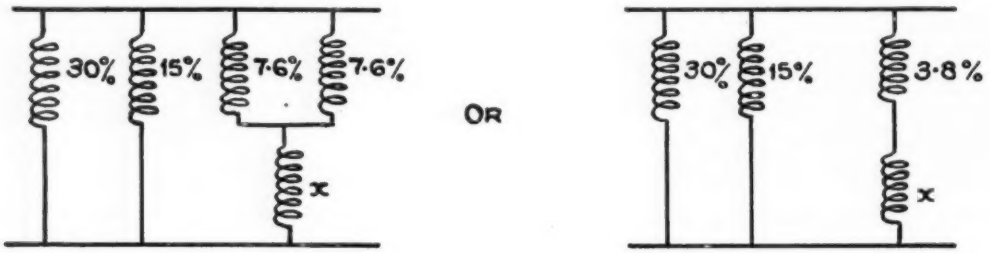
The following example illustrates the calculation of the size of reactor required in a certain application which is typical of many cases now arising. It is assumed that a small generating station is arranging to take a bulk supply from the Grid through step-down transformers and switchgear on to a new busbar, but it is desired to be able to feed on to the station busbar and thence to the old feeders through the existing switchgear. The latter has a rupturing capacity of only 150,000kVA. and calculation shows that under the new conditions a reactor must be inserted between the old and new busbars. It is assumed that the worst condition is a symmetrical three-phase short circuit on one of the old feeders (F).

Schematic Diagrams



The * figures are reactance values on a basis of 7,500 kVA.

Simplified Diagrams



Generators alone :

$$\text{Resultant Reactance} = \frac{1}{\frac{1}{30}+\frac{1}{15}} = \frac{1}{\cdot033+\cdot067} = 10\%$$

$$\text{Short Circuit kVA.} = \frac{100}{10} \times 7{,}500 = 75{,}000\ kVA.$$

Transformers alone (without reactor) :

$$\text{Resultant Reactance} = \frac{1}{\frac{1}{7\cdot6}+\frac{1}{7\cdot6}} = \frac{1}{\cdot132+\cdot132} = 3\cdot8\%$$

$$\text{Short Circuit kVA.} = \frac{100}{3\cdot8} \times 7{,}500 = 197{,}000\ kVA.$$

Generators and Transformers together (without reactor) :

$$\text{Resultant Reactance} = \frac{1}{\frac{1}{10}+\frac{1}{3\cdot8}} = \frac{1}{\cdot1+\cdot264} = 2\cdot75\%$$

$$\text{Short Circuit kVA.} = \frac{100}{2\cdot75} \times 7{,}500 = 273{,}000\ kVA.$$

To limit the Short Circuit kVA. to 150,000 kVA. the Total Resultant Reactance must not exceed

$$\frac{100}{150{,}000} \times 7{,}500 = 5\%$$

The value of reactance required in the reactor (x) may now be calculated as follows :

$$\frac{1}{10} + \frac{1}{3{\cdot}8 + x} = \frac{1}{5}$$

$$\therefore \quad \frac{1}{3{\cdot}8 + x} = \frac{1}{10}$$

$$\therefore \quad 3{\cdot}8 + x = 10$$

$$x = 6{\cdot}2$$

Check Calculation :

$$\text{Total Resultant Reactance} = \frac{1}{\frac{1}{10} + \frac{1}{3{\cdot}8 + 6{\cdot}2}} = \frac{1}{{\cdot}1 + {\cdot}1} = 5\%$$

$$\text{Short Circuit kVA} = \frac{100}{5} \times 7{,}500 = 150{,}000\ kVA.$$

The proportions of this total Short Circuit kVA. supplied from the two sources are :—

$$\text{Generators} \quad \frac{100}{10} \times 7{,}500 = 75{,}000\ kVA.$$

$$\text{Transformers} \quad \frac{100}{3{\cdot}8 + 6{\cdot}2} \times 7{,}500 = 75{,}000\ kVA.$$

(It is only a coincidence that the proportions are equal.)

In the above calculations it is assumed that the equivalent reactance of the Grid supply system up to the step-down transformers may be neglected.

It is required to give a supply of only 6,000 kVA. from the Grid to the old busbar, and, consequently, the reactor must be designed for a continuous current rating corresponding to 6,000 kVA. and a reactance of $6.2 \times \frac{6{,}000}{7{,}500} = 4.95\%$, and under short-circuit conditions it must be capable of carrying 75,000 kVA. for a period determined by the setting of the circuit breakers, say, 5 seconds.

The system is three-phase 50 cycles and 3,300 volts. The characteristics of the reactor would be as follows :—

$$\text{Continuous Current Rating} = \frac{6{,}000 \times 1{,}000}{3{,}300 \times 1{\cdot}73} = 1{,}050\ amps.$$

$$\text{Reactance Voltage per phase} \ldots 4{\cdot}95\% \text{ of } \frac{3{,}300}{1{\cdot}73} = 94\ volts.$$

$$\text{Equivalent Capacity} = 4{\cdot}95\% \text{ of } 6{,}000 = 297\ kVA.$$

$$\text{or} = 1{,}050 \times 94 \times 3 = 297\ kVA.$$

$$\text{Reactance per phase} = \frac{94}{1{,}050} = {\cdot}0895\ ohm.$$

$$\text{Short Circuit Current} = \frac{75{,}000 \times 1{,}000}{3{,}300 \times 1{\cdot}73} = 13{,}200\ amps.$$

$$= 12{\cdot}6\ times\ F.L.\ current.$$

This reactor would be of the oil-immersed iron-clad type, three separate single-phase coils being mounted one above the other in the same tank. The total weight would be about 8,200 lb., and the approximate overall dimensions would be 56 inches diameter, and 124 inches high. The loss under the continuous current rating condition of 297 kVA. would be about 12,600 watts for the three-phase unit.

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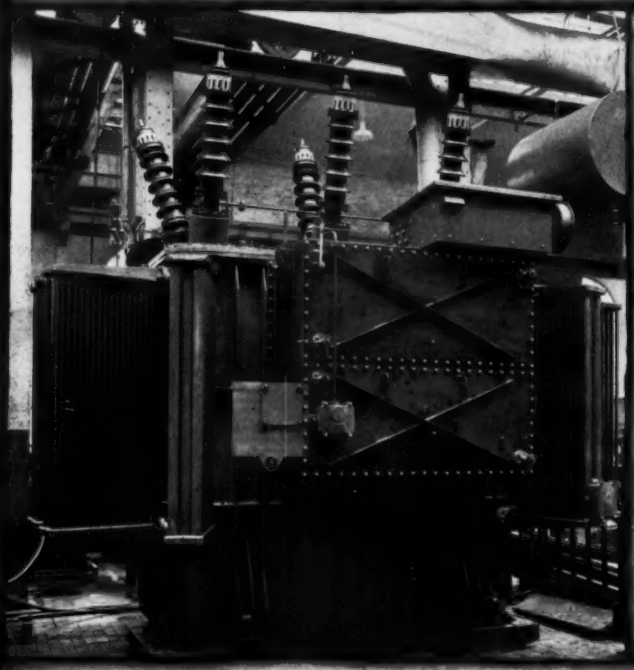

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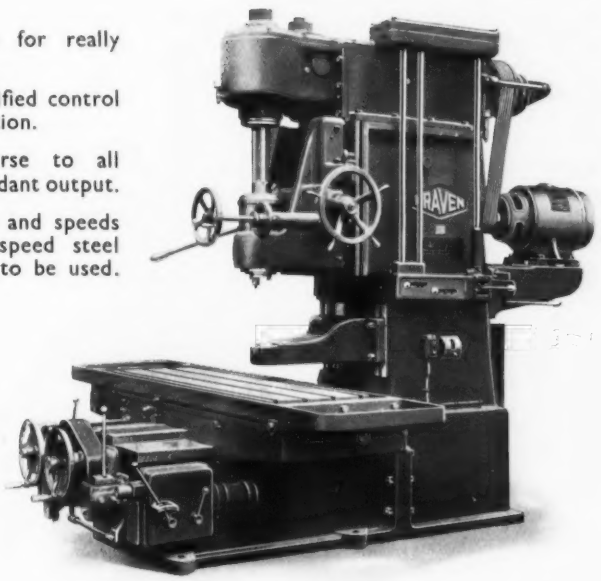

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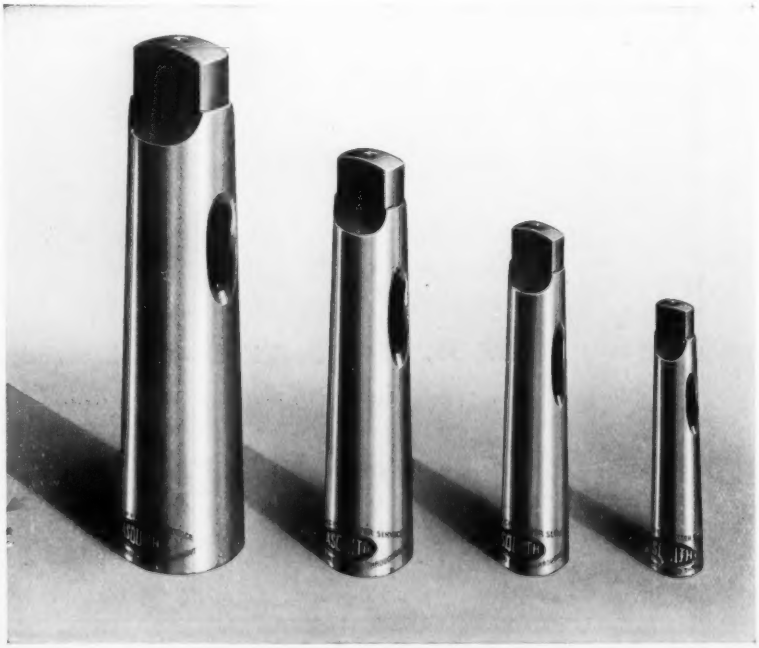

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